

# A Hidden Local Symmetry Approach to Rho Meson Photoproduction

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## Abstract

We study photoproduction of  $\rho$  mesons in a model of hidden local symmetry. The  $\rho$  meson is introduced as a hidden gauge boson and a phenomenological  $\rho$  meson-nucleon Lagrangian is constructed respecting chiral symmetry. It is shown that the  $\sigma$  exchange interaction is needed for neutral  $\rho$  meson photoproduction to reproduce the experimental cross sections. For charged  $\rho$  meson photoproduction, the model takes into account the  $\rho$  meson magnetic moments from the three-point vertex in the kinetic terms. We show that the magnetic moment of the charged  $\rho$  meson has a significant effect on the total cross sections through the  $\rho$  meson exchange process, which is proportional to the energy of the photon. The  $t$ -channel dominance may be used for the study of structures of various unstable particles.

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## I. INTRODUCTION

Vector mesons play important roles in hadron physics. For instance, they are responsible for the short range part of the nuclear force and also explain electromagnetic properties of hadrons through the vector meson dominance model [1–3]. They have been studied in the quark model as  $q\bar{q}$  states, while in field theoretical approaches they are regarded as gauge bosons of certain gauge symmetries. The  $\rho$  meson has been introduced as a gauge boson of the Hidden Local Symmetry (HLS) of the non-linear  $\sigma$  model which has explained many celebrated low energy relations [4, 5]. Also, a holographic model in the string theory provides a systematic derivation of the series of vector mesons [6, 7]. Another recent development is to regard a vector meson as one of the building blocks of the so called molecular-resonance states. Some studies have been done for the  $\rho$ -N(nucleon) systems and their extensions [8–10]. They are considered as candidates of non-conventional multi-quark states in the quark model. Such resonant states may be considered as strongly correlated three-body states due to the  $\rho$  meson decay into two pions.

Since vector mesons are unstable, only production reactions can provide information on their structure and interaction with the other hadrons. Among them, photoproduction is the most useful because, through vector meson dominance, the real photon may convert into a virtual vector meson which successively interacts with the nucleon. Photoproduction of a neutral  $\rho$  meson can easily be measured using the decay of the  $\rho^0$  into two charged pions  $\pi^+\pi^-$  [11, 12].

In this paper, we investigate  $\rho$  meson photoproduction for the study of the  $\rho$  meson dynamics based on the symmetries of the strong interaction. For this purpose, we employ the HLS model. It turns out that this model by itself can not explain the production rate as observed in experiments. Therefore, we follow previous work [13] and introduce the  $\sigma$  meson exchange in a phenomenological manner. We also investigate charged  $\rho$  meson production where we propose a method to study the unknown magnetic moment of the  $\rho$  meson. This is possible if the reaction mechanism is dominated by  $\rho$  meson exchange in the  $t$ -channel as expected in the forward region.

## II. MODEL

Let us introduce the HLS Lagrangian based on the non-linear  $\sigma$  model with the vector mesons, which is given by

$$\mathcal{L}_{\text{HLS}} = -\frac{1}{2}\text{Tr}F_{\mu\nu}^2 + a\mathcal{L}_V + \mathcal{L}_A, \quad (1)$$

where

$$\mathcal{L}_V = -\frac{f_\pi^2}{4}\text{Tr}\left[(\partial_\mu\xi^\dagger - igV_\mu\xi^\dagger + ie\xi^\dagger A_\mu)\xi + (\xi \leftrightarrow \xi^\dagger)\right]^2, \quad (2)$$

$$\mathcal{L}_A = -\frac{f_\pi^2}{4}\text{Tr}\left[(\partial_\mu\xi^\dagger - igV_\mu\xi^\dagger + ie\xi^\dagger A_\mu)\xi - (\xi \leftrightarrow \xi^\dagger)\right]^2. \quad (3)$$

Here we follow the notations for the fields and the normalization from Ref. [4]. For instance, the isospin structure is given by

$$V^\mu = \frac{\vec{\tau}}{2} \cdot \vec{V}^\mu, A^\mu \rightarrow \frac{\tau^3}{2} A^\mu, \pi = \frac{\vec{\tau}}{2} \cdot \vec{\pi} \text{ and } \xi = \exp(i\pi/f_\pi), \quad (4)$$

with  $f_\pi$  being the pion decay constant. We also include, in addition to the  $\rho$  meson field  $V^\mu$ , the photon field  $A^\mu$ . The anomalous term generates the isoscalar photon coupling to the  $\omega$  meson. Then the relevant terms for photoproduction are

$$\mathcal{L}_{V\gamma} = -e\frac{m_V^2}{g}A^\mu\left(\rho_\mu^3 + \frac{1}{3}\omega_\mu\right), \quad (5)$$

$$\mathcal{L}_{VVV} = -2ig\text{Tr}(\partial_\mu\rho_\nu[\rho^\mu, \rho^\nu]), \quad (6)$$

$$\mathcal{L}_{\omega\pi\rho} = g_{\omega\rho\pi}\epsilon_{\mu\nu\rho\sigma}\partial^\mu\vec{\rho}^\nu\partial^\rho\omega^\sigma\vec{\pi}. \quad (7)$$

The  $\omega$  meson coupling is given by  $g_{\omega\rho\pi} = -3g^2/8\pi^2 f_\pi$  [14].

As far as neutral  $\rho$  meson photoproduction is concerned, it turns out that the above ingredients are not enough to reproduce the experimental data using these interactions. To explain the observed strength, the scalar isoscalar  $\sigma$  meson was introduced in Ref. [13]. We adopt the phenomenological Lagrangian given by

$$\mathcal{L}_{\sigma\rho\rho} = \frac{g_{\sigma\rho\rho}}{m_\rho}\sigma\left(\partial_\mu\rho_\nu^0\partial^\mu\rho^{\nu 0} - \partial_\mu\rho_\nu^0\partial^\nu\rho^{\mu 0}\right). \quad (8)$$

For photoproduction off a nucleon,  $\rho NN$ ,  $\sigma NN$  and  $\pi NN$  interaction vertices are needed:

$$\mathcal{L}_{\rho NN} = -g_{\rho NN}\bar{N}\left(\gamma_\mu\rho^\mu + \frac{\kappa_\rho}{4M}\sigma^{\mu\nu}F_{\mu\nu}\right)N, \quad (9)$$

$$\mathcal{L}_{\sigma NN} = g_{\sigma NN}\sigma\bar{N}N, \quad (10)$$

$$\mathcal{L}_{\pi NN} = -2ig_{\pi NN}\bar{N}\gamma_5\pi N. \quad (11)$$

One would expect that the  $\sigma$  meson could be incorporated in the model by introducing the scalar fluctuation,  $f_\pi \rightarrow f_\pi + \sigma$ . As shown in Fig.1, this produces two amplitudes involving the  $\sigma$ -exchange, which however cancel exactly. For the  $\pi NN$  vertex we have adopted the pseudo-scalar coupling, which is equivalent to the pseudo-vector coupling for on-shell nucleons as is the case when the  $\pi$  appears in the  $t$ -channel. The Lagrangians Eqs. (5)–(10) complete all the necessary interactions in the present analysis. The needed parameters are given in Table I.

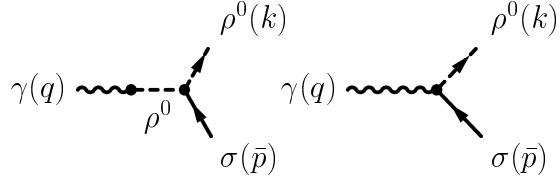


FIG. 1. The vertices of  $\gamma\sigma\rho$  in the hidden local symmetry approach.

TABLE I. Coupling constants for various interactions.

$e^2/4\pi$	$g (= g_{\rho NN})$	$f_\pi$ (MeV)	$g_{\pi NN}$	$g_{\sigma NN}$	$g_{\sigma\rho\rho}$	$\kappa_\rho$
1/137	5.85	93	13.26	10	11	3.7

TABLE II. Masses and cutoff parameters in the present calculation (MeV).

$m_\pi$	$m_\sigma$	$m_\rho$	$m_\omega$	$M_N$	$\Lambda$	$\Lambda_\sigma$	$\Lambda_{\sigma\rho\rho}$
137	500	770	782	938	800	900	700

Having the above interactions, one can obtain the tree-level amplitude as a sum of the  $s$ -channel,  $t$ -channel ( $\pi$ ,  $\sigma$ ,  $\rho$  exchange),  $u$ -channel and contact terms as shown in Fig. 2. The  $s$ -channel amplitude, for instance, is given by

$$\begin{aligned} \mathcal{M}_s = & -eg_{\rho NN}\bar{u}_p(p') \left( \not{\epsilon}^*(k) + \frac{\kappa_\rho}{2M_N} \sigma_{\mu\nu}(ik^\nu \epsilon^{\mu*}(k)) \right) \\ & \times \frac{i(\not{p} + M_N)}{\not{p}^2 - M_N^2} \left( \not{\epsilon}^\gamma(q) + \frac{\kappa_p}{2M_N} \sigma_{\mu\nu}(-iq^\nu \epsilon^\gamma(q)) \right) u_p(p), \end{aligned} \quad (12)$$

where the vectors  $\epsilon_\mu^\gamma$  and  $\epsilon_\mu$  are photon and  $\rho$  meson polarization vectors. Here the amplitude  $\mathcal{M}_s$  is defined by the  $S$ -matrix through  $S = 1 + \mathcal{M}_s$ . In this calculation we introduce form

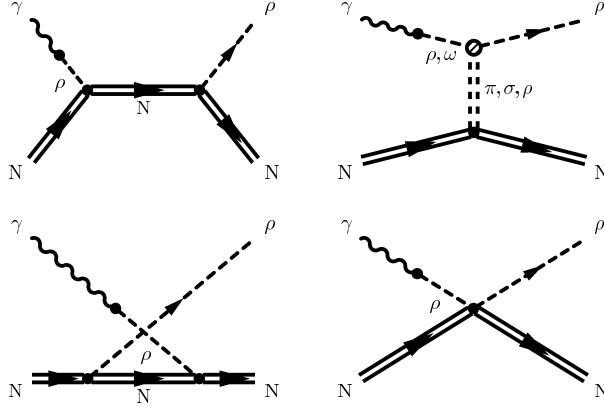


FIG. 2. Feynman diagrams for the tree-level model: double line presents nucleon, wavy line is photon, dashed line is  $\rho$  meson, double dashed line is  $\pi$ ,  $\sigma$  and  $\rho$  mesons.

factors following the prescription of Davidson and Workman [15]. For all ( $s$ ,  $t$  and  $u$ ) channels, the amplitudes are separated into gauge-invariant and non gauge-invariant parts. The sum of the non gauge-invariant parts is, however, gauge-invariant. Therefore, we multiply the form factors  $F_s$ ,  $F_u$  and  $F_t$  to the corresponding gauge-invariant parts of  $s$ ,  $t$  and  $u$ -channels, and  $F_c$  (common form factor) to the sum of the non gauge-invariant parts. We employ the  $s$ ,  $t$ ,  $u$ -channel form factors as

$$F_x = \frac{\Lambda^4}{\Lambda^4 + (M_x^2 - q)^2}, \quad x = s, t, u, \quad (13)$$

where  $M_x$  is the mean of particle in the channel  $x$ , while for the common form factor

$$F_c = F_s + F_t + F_u - F_s F_t - F_t F_u - F_s F_u + F_s F_t F_u. \quad (14)$$

For the  $\sigma$  exchange  $t$ -channel, we employ a form factor as

$$F_\sigma = \frac{\Lambda_\sigma^2 - m_\sigma^2}{\Lambda_\sigma^2 - q^2} \frac{\Lambda_{\sigma\rho\rho}^2 - m_\sigma^2}{\Lambda_{\sigma\rho\rho}^2 - q^2}. \quad (15)$$

The cutoff parameters in the form factors are given in Table II. These values are consistent with a finite size of hadrons of about 0.5 fm, which is related to the cutoff parameter  $\Lambda$  by  $r \sim \sqrt{6}/\Lambda$  [16].

### III. RESULTS AND DISCUSSION

First, we discuss differential and total cross sections for neutral  $\rho$  meson photoproduction in comparison with experimental data which has been taken from Ref. [11]. As anticipated in

Ref. [13], the phenomenological  $\sigma$  meson exchange in the  $t$ -channel plays a dominant role. It is consistent with the observed data which shows strongly forward peaking as shown in the left panel of Fig. 3. We also show various contributions separately; we see that the  $\sigma$  exchange dominates except for the backward region, where the  $u$ -channel process becomes important. The energy dependence of the total cross section is shown in the right panel of Fig. 3. The present calculation provides a smooth energy dependence; from the threshold it increases as the phase space volume increases and then turns to decrease gradually above  $E_\gamma \sim 1.5$  GeV, partly due to the form factors. On the contrary, experimental data shows a peak structure at around  $E_\gamma \sim 1.5 - 1.7$  GeV, depending on the method of data analysis. This is perhaps due to nucleon resonances which couples to the  $\rho$  meson. Neglecting possible resonance contributions, we can say that the agreement of the present model with the experimental data is fair up to  $E_\gamma \sim 3$  GeV. Above this energy, the experimental data seems rather flat up to 4 GeV, while the present result keeps decreasing. The energy  $E_\gamma \sim 3$  GeV is already about 2 GeV above the threshold, which is beyond the limitation of the present model.

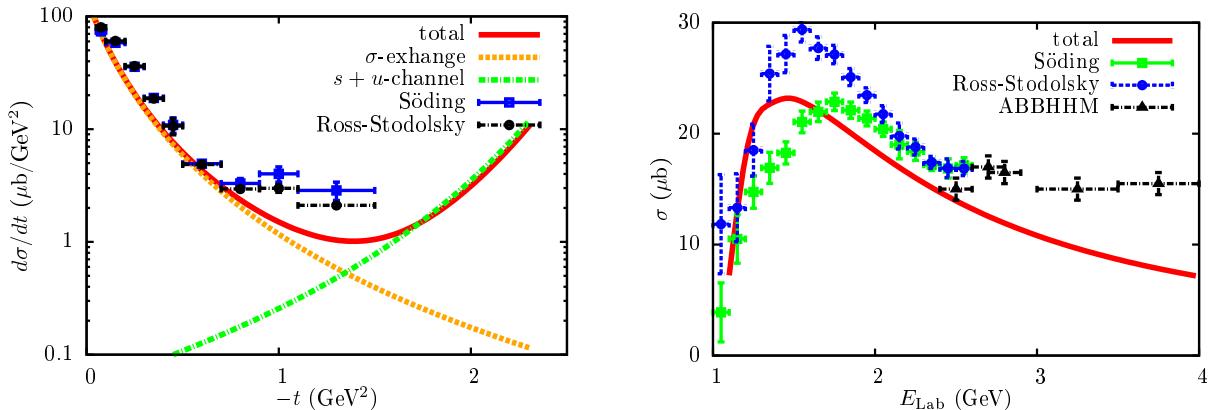


FIG. 3. Differential and total cross sections of the  $\gamma p \rightarrow \rho^0 p$  reaction as compared to the experimental data [11, 12, 17, 18]. The differential cross section is plotted as a function of the transferred momentum  $t$  at  $E_\gamma = 2$  GeV.

Let us now turn to the charged  $\rho$  meson photoproduction. For the reaction  $\gamma n \rightarrow \rho^- p$  the  $\sigma$  meson exchange process is not allowed but instead charged  $\rho$  meson exchange is. In the HLS model, the  $\gamma \rightarrow \rho^+ \rho^-$  amplitude is given by the vector meson dominance  $\gamma \rightarrow \rho^0$  and the successive three-point vertex of  $\rho^0 \rho^+ \rho^-$ . We find that in the  $\rho^-$  photoproduction the  $\rho$  meson exchange process has the largest contribution, and therefore this process is sensitive

to the  $\gamma \rightarrow \rho^+ \rho^-$  vertex. Since the  $\rho$  meson is a spin one particle there are three multipole components possible: electric, magnetic and quadrupole couplings [19]. The strength of the electric coupling is unambiguously determined by the charge due to the gauge symmetry, while those of the higher multipoles are not subject to the symmetry and can take an arbitrary strength. At low energies the electric coupling, the lowest multipole, dominates but as the photon energy is increased the higher multipoles become more important as they contain the photon momentum in their couplings. Here, for simplicity, we consider only the effects of the lowest two multipoles. Ignoring the effects of the quadrupole moment corresponds to assuming that spatial deformation of the  $\rho$  meson is not large [20].

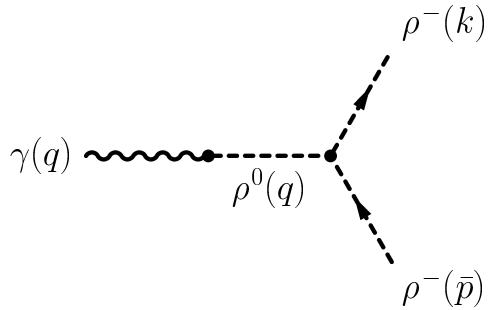


FIG. 4. The  $\gamma\rho\rho$  vertices based on HLS model

To illustrate the role of the magnetic moment of the  $\rho$  meson, let us look at the  $\gamma\rho\rho$  vertex and its contribution to the photoproduction through the  $t$ -channel  $\rho$  meson exchange diagram (Fig. 4). The vertex is given as

$$\begin{aligned} \Gamma_{\text{HLS}} = ie\{ & 2\epsilon^\gamma(q) \cdot k \epsilon^*(k) \cdot \epsilon(\bar{p}) \\ & + q \cdot \epsilon^*(k) \epsilon^\gamma(q) \cdot \epsilon(\bar{p}) - k \cdot \epsilon(\bar{p}) \epsilon^\gamma(q) \cdot \epsilon^*(k) \\ & + q \cdot \epsilon^*(k) \epsilon^\gamma(q) \cdot \epsilon(\bar{p}) - q \cdot \epsilon(\bar{p}) \epsilon^\gamma(q) \cdot \epsilon^*(k) \} . \end{aligned} \quad (16)$$

The momentum  $k$ ,  $q$  and  $\bar{p}$  are defined in Fig. 4. The first term is the electric coupling, while the third term is the magnetic one. The second term is similar to the magnetic coupling, and in fact, it coincides the third term when the two  $\rho$  mesons are on mass-shell. Furthermore, one can verify that the contributions of the second and the third terms to the photoproduction process in the  $t$ -channel  $\rho$  meson exchange diagram also coincide. Therefore, the  $t$ -channel  $\rho$  meson exchange contributions are divided into the electric one with the first term of Eq. (16), and magnetic one with the second and the third terms. Now the magnetic moment of the  $\rho$

meson in the HLS model, the sum of the two terms of Eq. (16), is given in the non-relativistic limit as

$$-\frac{\mu}{2m_V} \vec{q} \times \vec{\epsilon}^\gamma \cdot \vec{S}_\rho, \quad (17)$$

where  $\mu = 2$  and  $\vec{S}_\rho$  is the spin operator for the  $\rho$  meson. The factor  $1/2m_V$  appears when the normalization of the  $\rho$  meson wave function is taken into account properly. In general, the magnetic moment  $\mu$  reflects the information of the internal structure of the  $\rho$  meson and can take any value. Therefore, to see the role of the magnetic moment in photoproduction, we treat  $\mu$  as a parameter. In the minimal gauge coupling of the photon to the  $\rho$  meson one has  $\mu = 1$ . In the naive constituent quark model where the quark mass is half of the mass of the  $\rho$ ,  $m_q \sim m_V/2$ ,  $\mu = 2$ , which coincides the value of the HLS model.

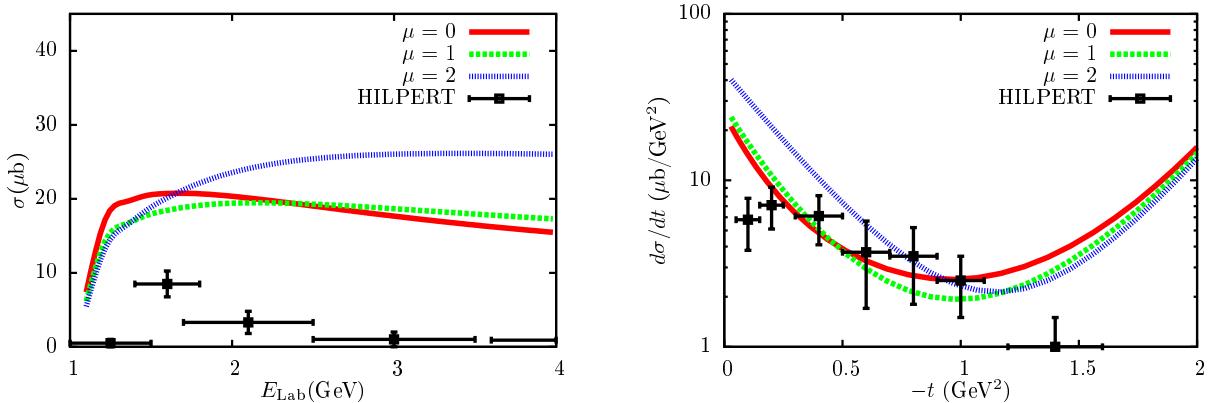


FIG. 5. Total and differential cross sections of the  $\gamma n \rightarrow \rho^- p$  reaction with different value of  $\mu = 0, 1, 2$ . The experimental data are taken from Ref. [21] and the differential cross section is plotted as the transferred momentum  $t$  dependence at  $E_\gamma = 2$  GeV. The results for  $\mu = 2$  corresponds to those of the HLS model.

In Fig. 5, we show the results for the total and differential cross sections for magnetic moment values  $\mu = 0, 1, 2$  in units of  $\rho$  meson magneton  $e/2m_V$ . For the total cross section the agreement of our present study and experimental data is not very good. Indeed, the difference is increased ( $E_\gamma \geq 2$  GeV) as the photon energy is increased as expected from the structure of the magnetic coupling where the photon momentum is involved. For  $\mu = 0$ , the cross section is smallest, since the only electric coupling terms exist. With this value, the present calculation overestimates the experimental data by about factor two near the

threshold region,  $E_\gamma \sim 1.5$  GeV, while the data decrease rapidly beyond that energy and the difference with the calculation increases. If  $t$ -channel exchange mechanism dominates, however, this result seems natural, because the cross section is roughly proportional to  $s^J$  where  $J$  is the spin of the exchanged particle.

Turning to the  $t$ -dependence (angular distribution), the  $\rho$ -exchange process exhibits a strong forward peak as shown in the right panel of Fig. 5 irrespective of the value of the magnetic moment  $\mu$ . This again seems contradictory to experimental data, which is rather flat for small  $|t|$  and decreases for  $|t| \geq 0.2$  GeV $^2$ . In the present calculation there are not many parameters to adjust the energy and  $t$  dependence of the cross section, and therefore, our result for the  $\rho$ -exchange amplitude is rather constrained.

To investigate the origin of the strong forward peaking predicted by our calculation, we have checked the various contributions to the cross section. This shows that the forward contribution is partly due to the magnetic contribution of the  $t$ -channel  $\rho$  meson exchange. Another important contribution is from the magnetic (tensor) coupling of the  $\rho$  meson with the nucleon with the strength  $\kappa_\rho$ . To investigate these points quantitatively we show in Fig. 6. the results of calculations where we set the  $\rho$  magnetic moment,  $\mu$ , equal to zero, combined with setting  $\kappa_\rho$  equal to zero. As can be seen the vanishing cross section at forward angles is reproduced only when both  $\mu = 0$  and  $\kappa_\rho = 0$ , though there remains still a discrepancy at backward angles, where in our calculation the  $u$ -channel process contributes significantly. The null values of  $\mu$  and  $\kappa_\rho$  are in clear contradiction with the predictions of the meson chiral model.

Our calculations form a strong motivation to improve the existing data base for photoinduced charged  $\rho$  meson production as this is very sensitive to the magnetic moment. Since a neutron target is not available for this work one has to perform experiments on the deuteron for which the application of the minimum spectator method is applied to obtain better kinematical constraints [22]. In addition it is important to have more accurate data for  $t \geq 1.1$  GeV $^2$ .

#### IV. CONCLUSIONS

We have studied photoproduction of a  $\rho$  mesons based on a chiral model with vector mesons introduced in the HLS model supplemented by a  $\sigma$  meson exchange. The production

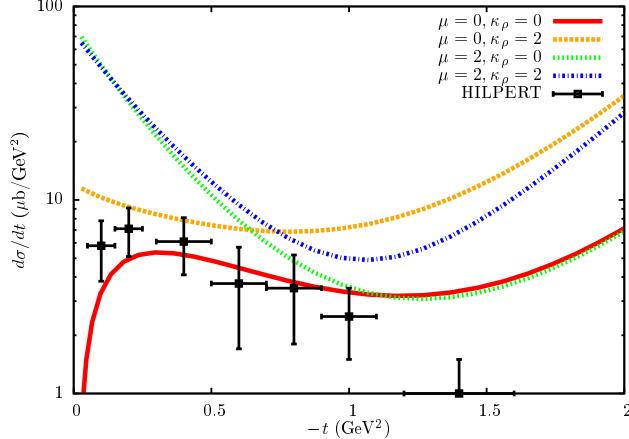


FIG. 6. Differential cross sections of the  $\gamma n \rightarrow \rho^- p$  reaction with different value of  $\mu = 0, 2$  and  $\kappa_\rho = 0, 2$ . the differential cross section is plotted as the transferred momentum  $t$  dependence at  $E_\gamma = 2$  GeV and the cutoff parameter at  $\Lambda = 1.1$  GeV.

of the neutral  $\rho$  meson is reasonably explained by the  $\sigma$  meson exchange, while for the charged  $\rho$  meson photoproduction we have shown that the  $\rho$  meson exchange in the  $t$ -channel is the dominant contribution. The dominance of the  $t$ -channel gives rise to an angular distribution with a strong forward peak, in disagreement with the presently available data. For charged  $\rho$  meson production a neutron target is necessary. For this, we pointed out that application of the minimum momentum spectator method may be used to achieve good kinematics in experiment. The cross section was then shown to be dependent sensitively on the magnetic moment of the  $\rho$  meson and on the tensor coupling of the  $\rho$  meson with the nucleon. Such a study of  $t$ -channel dominant process is useful to obtain information of magnetic moment which reflects the internal structure of an unstable particle.

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